Fermi National Accelerator Laboratory

FERMILAB-Conf-95/053-E
E769

Current Issues in Open Charm Hadroproduction and New Preliminary Results from Fermilab E769

Paul E. Karchin
For the E769 Collaboration

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

March 1995

To appear in the proceedings of the *LAFEX International School on High Energy Physics (LISHEP95)*, CBPF, Rio de Janeiro, February 6-22, 1995

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CHO3000 with the United States Department of Energy

Current Issues in Open Charm Hadroproduction and New Preliminary Results from Fermilab E769

Paul E. Karchin
Yale University

Abstract

We review the experimental data on total charm cross section, fragmentation into charm species, dependence of the charm cross section on beam flavor, atomic mass, and transverse momentum, charm pair correlations, and leading particle asymmetry. Included are new preliminary results from Fermilab experiment E769.

Introduction

At the collision energies achieved in modern fixed target experiments, charm quarks are predominantly produced from gluon-gluon collisions where one gluon originates from each of the initial state hadrons. The production cross section thus depends on the combination of the gluon distributions of the colliding hadrons and the partonic cross section. However, the measurable cross sections are for charm particles, not charm quarks. The fragmentation process by which the charm quarks combine with light quarks to form the final state hadrons determines the fractions of the various charm species. Because the charm quark mass is large compared to the QCD scale factor Λ_{QCD}, the cross section for charm quark production is treated using QCD perturbation methods. In contrast, the fragmentation process involves small momentum transfers compared to Λ_{QCD} and is treated using phenomenological methods often implemented by Monte Carlo algorithms.

An interesting aspect of the fragmentation process is the extent to which spectator valence quarks from the initial state hadrons combine with the produced charm quarks. For example, in a fixed target experiment with a π^- beam, an anti-charm quark with positive Feynman-x (x_F) can combine with a d quark from the π^- to form a final state D^- with $x_F > 0$. However, there is no forward moving $\overline{d}$ with which a forward moving c quark can form a forward moving D^+. Thus, the cross section for D^- would be larger than for D^+ if this mechanism takes place. Only a small asymmetry between forward c and $\overline{c}$ quark production is expected from QCD. For a π^- beam, some leading charm mesons are D^-, $\overline{D}^0$ and D^{*-}, while non leading ones are D^+, D^0, and D^{*-}.

Experiments contributing to the modern data on open charm hadroproduction are summarized in Table 1. Included are experiments which have published results, reported preliminary data, or are approved for future data taking. The year indicates when data was taken or is planned to be taken. This table is an updated, but abbreviated version of the one in the 1992 review by Appel [1]. These experiments encompass a variety of techniques.

Table 1: Experiments contributing to the modern data on open charm hadroproduction. Included are experiments which have published results, reported preliminary data, or are approved for future data taking. The year indicates when data was taken or is planned to be taken.

Identifier	Number	Meson Beams			Baryon Beams		
		GeV	type	year	GeV	type	year
LEBC-EHS	NA16	360	π^-	82	360	p	82
	NA27	360	π^-	84	400	p	84
LEBC-MPS	E743				800	p	85
hybrid emulsion	E653	600	π^-	84-85	800	p	87-88
hybrid emulsion	WA75	350	π^-	82,83			
ACCMOR	NA32	200	π^-, K^-	84	200	p	84
		230	π^-	86			
TPL	E769	250	$\pi^\pm, K^\pm$	87-88	250	p	87-88
	E791	500	π^-	91			
Di-Hadron	E789				800	p	91
OMEGA	WA82	340	π^-	87-89	370	p	88-89
	WA89				330	Σ^-	91,93
	WA92	350	π^-	92,93			
SELEX	E781	550	π^-	96	550	p, Σ^-	96
HERA-B					820	p	99

The Lexan Bubble Chamber (LEBC) experiments at CERN and Fermilab employed a high resolution bubble chamber with an electronic spectrometer. Experiments WA75 at CERN and E653 at Fermilab utilized nuclear emulsion targets with electronic spectrometers. All the other experiments use fully electronic spectrometers with silicon strip vertex detectors. Most experiments use π^- and/or p beams, but some also use $K^\pm$, π^+ and Σ^- beams.

While this report gives an overview, there are certain omissions, covered by other speakers at this conference. The recent preliminary results from CERN WA89 on charm production with a Σ^- beam are reported by Hans-Wolfgang Siebert. Charmonium hadroproduction (closed charm) is discussed by Kwong Lau. A theoretical talk by Ramona Vogt includes a description of the contribution from intrinsic charm.

Total Charm Cross Section

The total charm cross section is the sum of the cross sections for the various charm species. A large subset of charm cross section data is for $x_F > 0$ for the mesons D^0, $\overline{D}^0$ and $D^{\pm}$. It is important to update the older measurements with current branching fractions so that the results of different experiments can be compared in a consistent way. To compare the measurements with theory, we employ a computer program from the collaboration of Frixione, Mangano, Nason and Ridolfi [2] which is based on next to leading order (NLO) QCD and employs structure functions reported in the literature. We use this program to predict the cross section for a c or $\bar{c}$ quark with $x_F > 0$. The biggest theoretical uncertainty is from the choice of the renormalization and factorization scales, μ_R and μ_F. The uncertainty in the cross section is at least as large as the variation over the range $m_c/2 < \mu_R < 2m_c$ where m_c is the charm quark mass. For the predictions presented here we used the fixed values $\mu_F = m_c = 1.5$ GeV. There is also uncertainty in the cross section due to the uncertainties in m_c and the structure functions for the initial state hadrons.

The QCD prediction for π^- beam is compared with data [3, 4, 5, 6, 7] in Figure 1. The cross section data include preliminary results from WA92 and E769. The data are consistent with the shape of the energy dependence of the QCD prediction. Note that the size of the D meson cross sections alone are comparable to that predicted for charmed quarks. Since the charm baryons will add to the total measured cross section, the central value for the NLO prediction is almost certainly too small, but consistent with the data given the large theoretical error. It can be seen from the curves for different values of μ_R that the shape versus energy of the prediction is relatively insensitive to the value of μ_R. The shape is also insensitive to the other factors contributing to the the theoretical uncertainty. More precise experimental data are required to test the prediction for the shape of the energy dependence of the cross section.

For a proton beam, the prediction and data [3, 8, 9, 10, 11] are shown in Figure 2. The comparison of data with theory is similar to that for the π^- beam: more precise measurements are needed to test the shape prediction. It is also interesting to compare the p and π^- induced cross sections. The theoretical prediction is that the π^- induced cross section is slightly larger than that for p. The data are not precise enough to measure this small difference.

Besides the above comparisons of the summed charm meson cross sections and theory, we've also looked at the separate data for charged and neutral charmed mesons. Generally, these data follow the same trend as the summed data, as would be expected under the reasonable assumption that fragmentation into a particular charmed species is independent of beam energy. However, one of these comparisons shows an anomaly: the p induced cross section

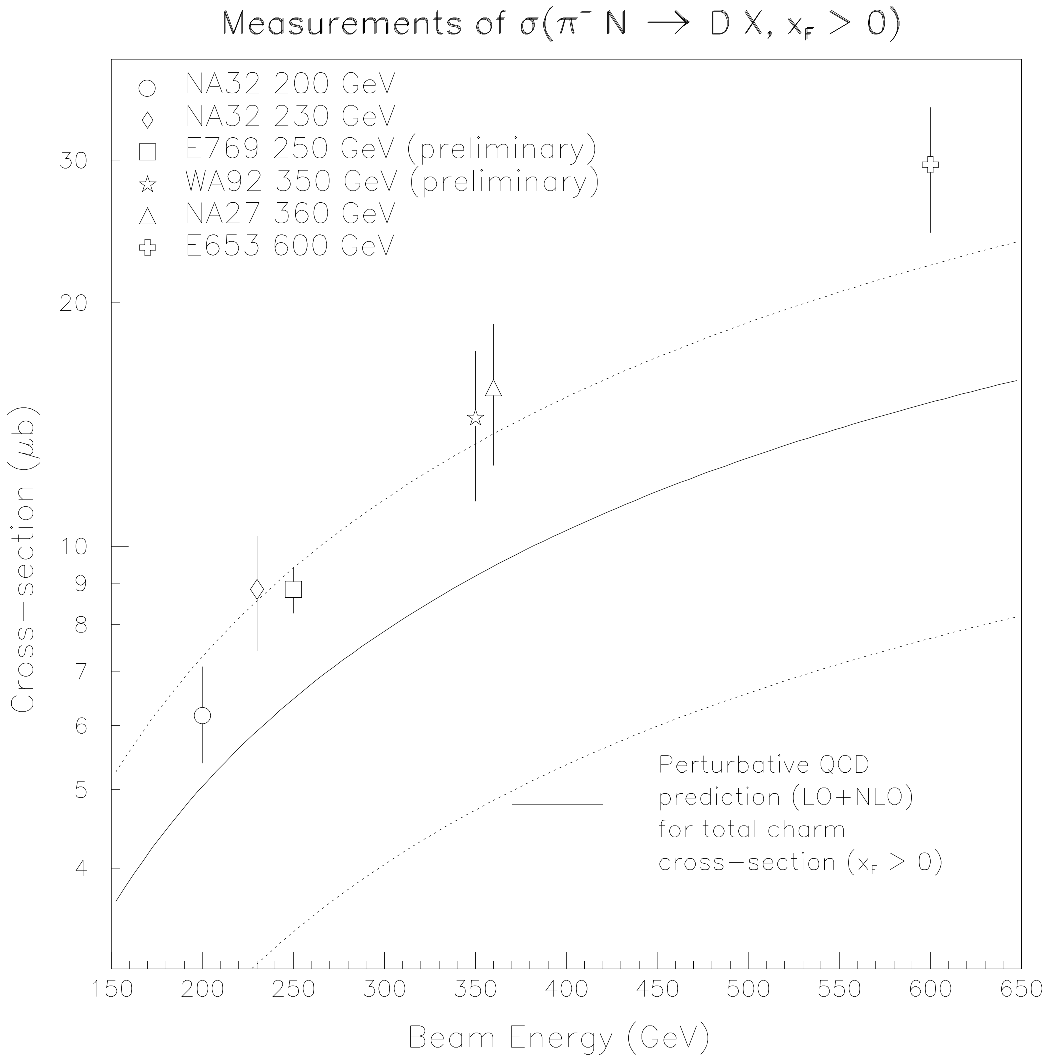

Figure 1: Measurements of the cross section per nucleon (assuming $\alpha = 1$) for D^0, $\overline{D}^0$ and $D^{\pm}$ production for $x_F > 0$ in π^--nucleon collisions. The errors shown are combined statistical and systematic errors, including the systematic errors due to branching fractions. Where necessary, current values for branching fractions (1994 PDG) were used to update published cross sections. The prediction for the charm quark cross section, for $x_F > 0$, is based on the computer program of Frixione, Mangano, Nason and Ridolfi with $m_c = \mu_F = 1.5$ GeV. Curves are shown for $\mu_R = m_c/2$, m_c, and $2m_c$.

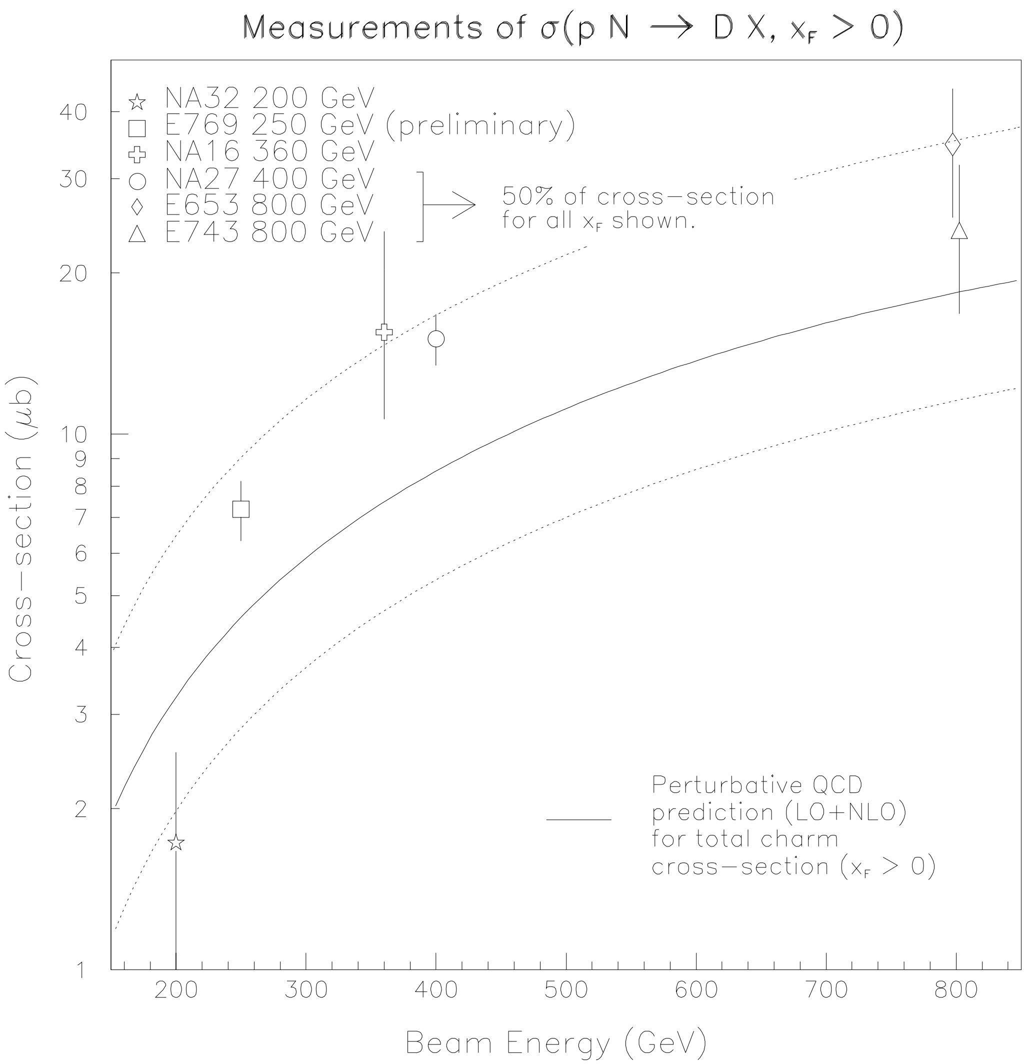

Figure 2: Measurements of the cross section per nucleon for D^0, $\overline{D}^0$ and $D^{\pm}$ production for $x_F > 0$ in p-nucleon collisions. See the explanatory notes for Figure 1.

for D^0 and $\overline{D}^0$ versus beam energy, as shown in Figure 3. The recent measurement from

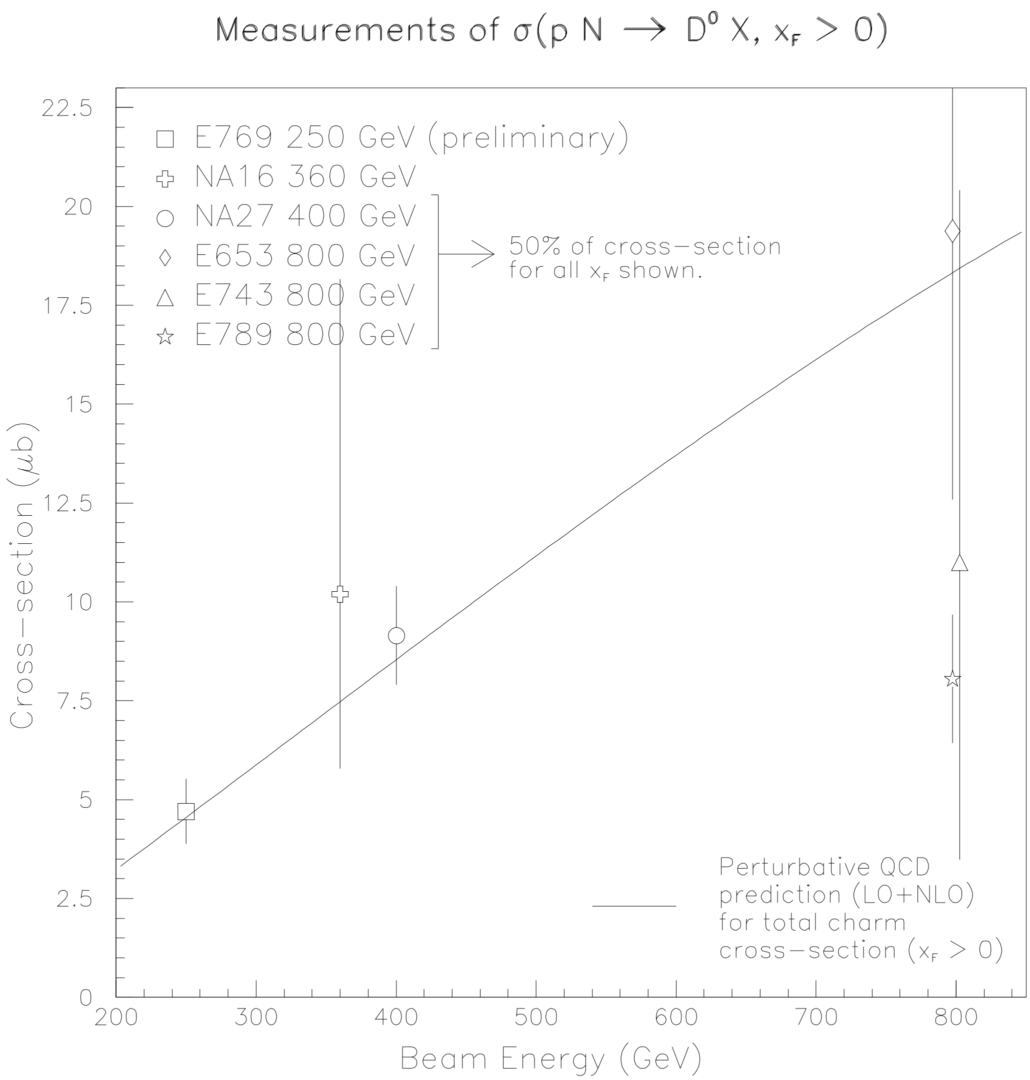

Figure 3: Measurements of the cross section per nucleon for D^0, $\overline{D}^0$ production for $x_F > 0$ in p-nucleon collisions. See the explanatory notes for Figure 1.

Fermilab E789 [12] is significantly lower than would be expected from the lower energy data extrapolated using the shape of the QCD prediction. One caveat is that E789 measures the cross section over the small range $0. < x_F < 0.08$. The cross section for $x_F > 0$ is found using the low statistics measurements of the shape of the differential cross section in x_F reported by E743 and E653. A measurement over a wide range of x_F of the $D^0, \overline{D}^0$ cross section using a proton beam near 800 GeV is needed to test this anomaly.

Species Fragmentation

There are fewer and less precise measurements of the cross section for charm species other than D^0, $\overline{D}^0$ and $D^\pm$. The data for π^- beam are presented in Figure 4 as ratios of cross sections involving D^0, $\overline{D}^0$, $D^\pm$, $D_s^\pm$, $D^{*\pm}$ and $\Lambda_c^\pm$. The measurements of $\sigma(D^0, \overline{D}^0)/\sigma(D^\pm)$ are

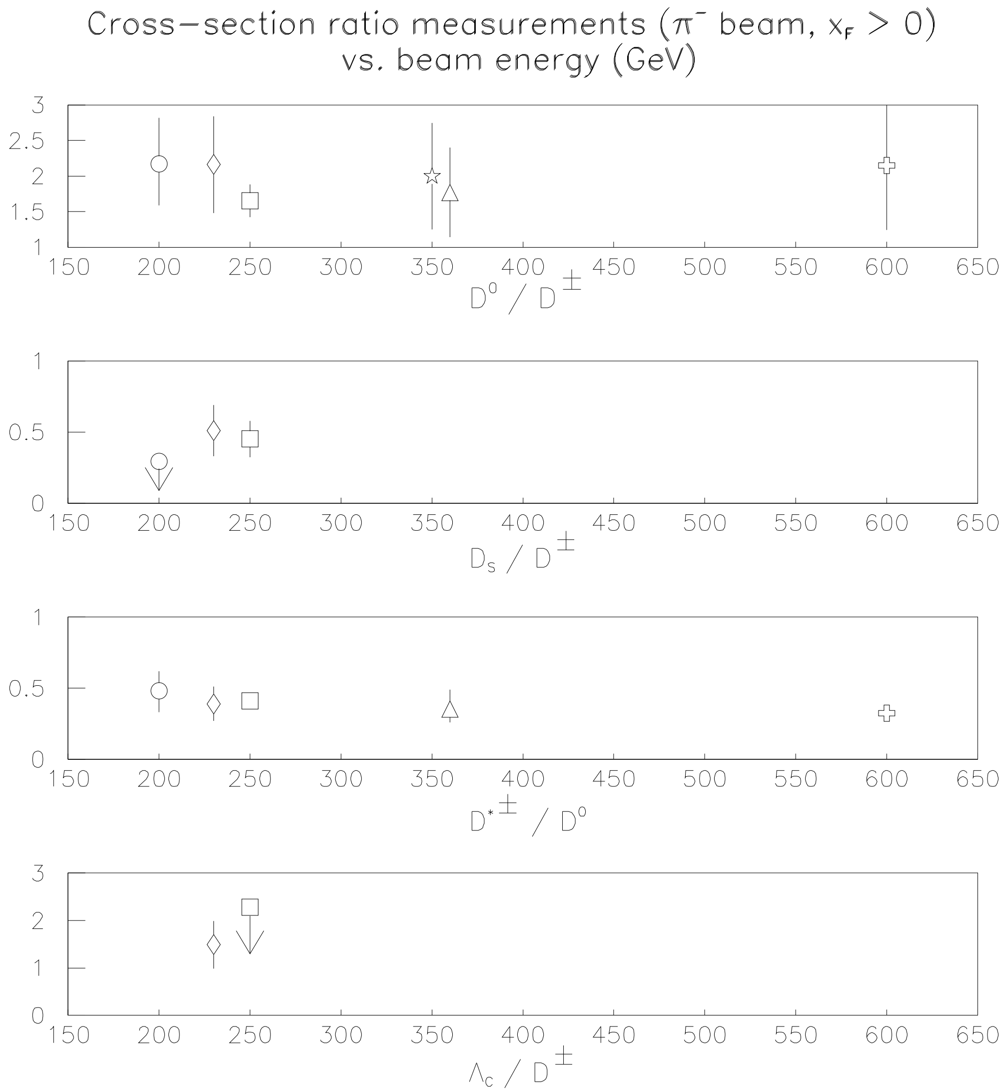

Figure 4: Ratios of cross section for various charm species produced in π^- - nucleon collisions. The beam energy is in GeV. The explanatory notes and symbol key of Figure 1 also apply here. All ratios include particles and charge conjugates.

in the range 1.5 - 2.5 over the span of beam momenta from 200 to 600 GeV. A simple model predicting cross sections in proportion to the number of spin states for D^0, $\overline{D}^0$, $D^\pm$ and $D^{*\pm}$ predicts a ratio of 3.1, clearly larger than the measurements. The data for $\sigma(D^0)/\sigma(D^\pm)$ are consistent with no dependence on beam energy. The data for $\sigma(D^{*\pm})/\sigma(D^0, \overline{D}^0)$ are in the range 0.3 - 0.5. The simple spin model predicts 0.50. The ratio $\sigma(D_s^\pm)/\sigma(D^\pm)$ is only measured by NA32 and E769. These measurements indicate a ratio of about 0.5. Thus, $D_s^\pm$ production is not highly suppressed by the requirement for production of a strange quark pair. The only measurements of $\Lambda_c^\pm$ production that include small x_F are from NA32 [14] and the preliminary limit from E769 of $\sigma(\Lambda_c^\pm)/\sigma(D^\pm) < 2.3$ at 90% C.L. The indication is that $\Lambda_c^\pm$ production is comparable to that for $D^\pm$.

For a proton beam, cross section ratios are shown in Figure 5. The few measurements

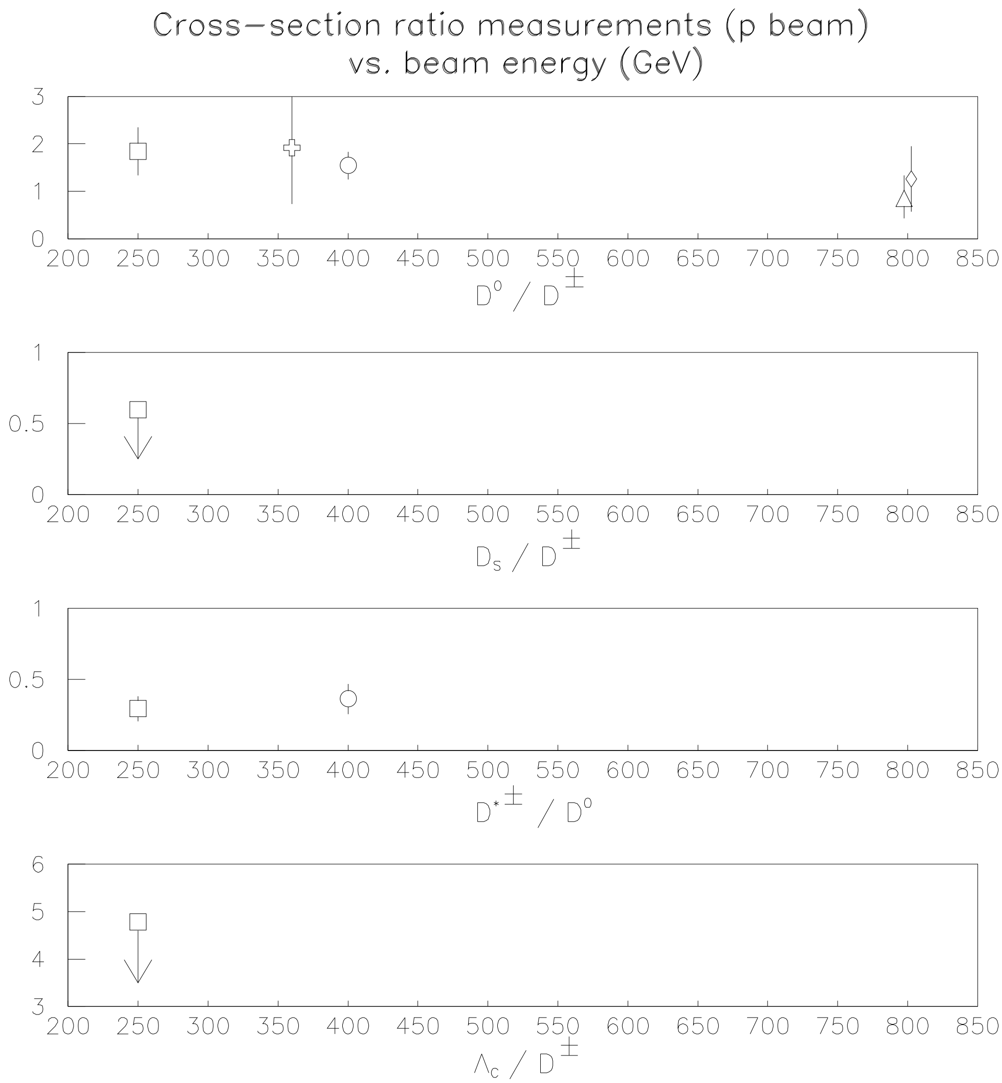

Figure 5: Ratios of cross section for various charm species produced in p - nucleon collisions. The beam energy is in GeV. The explanatory notes of Figure 1 and the symbol key of Figure 2 also apply here. All ratios include particles and charge conjugates.

available are consistent with the corresponding ratios for π^- beam.

Beam Flavor Dependence

For beams other than π^- and p, the only cross section measurements are from NA32 and the preliminary E769 results, all of which are given in Table 2. Both experiments have

Table 2: Forward $D^\pm$, D^0, and $D_s^\pm$ production cross sections (μb/nucleon, assuming $\alpha = 1$). E769 cross section results are preliminary. Each given cross section is the sum of those for the final state particle and anti-particle. Errors quoted are statistical and systematic, in that order; only statistical errors are shown for E769 D^0 and D_s results. The systematic errors do not include the error from the branching fraction. All cross sections shown assume PDG 1994 branching fractions.

Beam (B)	$\sigma(BN \to D^\pm X,\ x_F > 0)$		$\sigma(BN \to D^0 X,\ x_F > 0)$		$\sigma(BN \to D_s^\pm X,\ x_F > 0)$	
π^-	$2.0 \pm 0.4 \pm 0.1$	NA32 88	$4.2 \pm 0.6 \pm 0.4$	NA32 88	< 0.6 (90% C.L.)	NA32 88
	$2.7 \pm 0.2 \pm 0.6$	NA32 91	$6.1 \pm 0.3 \pm 1.2$	NA32 91	$1.4 \pm 0.2 \pm 0.2$	NA32 91
	$3.3 \pm 0.3 \pm 0.2$	E769	5.5 ± 0.4	E769	1.5 ± 0.3	E769
π^+	$3.4 \pm 0.4 \pm 0.4$	E769	5.9 ± 0.7	E769	2.3 ± 0.7	E769
K^-	$4.7 \pm 1.2 \pm 0.4$	NA32 88	$5.0 \pm 1.5 \pm 0.4$	NA32 88	$5.0 \pm 1.7 \pm 0.4$	NA32 88
					$2.3 \pm 1.2 \pm 0.4$	NA32 91
	$2.4 \pm 0.4 \pm 0.7$	E769	2.8 ± 1.0	E769	2.8 ± 1.0	E769
K^+	$2.7 \pm 0.4 \pm 0.4$	E769	4.4 ± 0.8	E769	2.2 ± 0.9	E769
p	$2.5 \pm 0.4 \pm 0.2$	E769	4.7 ± 0.8	E769	< 1.5 (90% C.L.)	E769

data for π^-, K^- and p beams. The only data for π^+ and K^+ beams are from E769. Both experiments report individual cross sections for D^0,$\overline{D}^0$, $D^\pm$, and $D_s^\pm$. The beam momentum was 200 or 230 GeV for NA32 and 250 GeV for E769. For the 230 GeV NA32 data and the 250 GeV E769 data, the cross sections measured by the two experiments are consistent for each beam type and final state particle. Furthermore, all cross section measurements are consistent with no dependence on the beam flavor. As noted before, the small difference in charm cross sections between pion and proton beam predicted by NLO QCD is below the current experimental sensitivity.

Atomic Mass Dependence

The charm cross section should be proportional to the atomic mass A of the target if production and fragmentation are short distances processes. The measurements are parameterized by $\sigma \propto A^{\alpha}$. There are three measurements [15, 16, 12] with exclusive charm signals as summarized in Table 3. These measurements are consistent with $\alpha = 1$, repre-

Table 3: Measurements of atomic mass dependence of the charm cross section.

Expt.	α
WA82	$0.92 \pm .06$
E769	$1.00 \pm .05$
E789	$1.02 \pm .04$

senting purely short distance behavior.

Transverse Momentum Dependence

The differential cross sections for charm particle production versus x_F and p_T provide further probes of the production mechanisms beyond the total cross sections. Here we point out some recent theoretical and experimental studies of the p_T dependence.

Frixione, Mangano, Nason and Ridolfi [2] found that the NLO QCD predictions for the p_T dependence of hadroproduced charm quarks are well parameterized by the formula,

$$\frac{d\sigma}{dp_T^2} = \left(\frac{c}{am_c^2 + p_T^2} \right)^{\beta}$$

where a, β and c are parameters. Using E769 data, we compare their predictions for charm quark production with pion and proton beams with measurements [17] for $D^{\pm}$, as shown in Figures 6 and 7. As seen in the figures, the theoretical predictions for quarks reasonably represent the data for particles. This agreement is well established in the literature. It remains an outstanding puzzle why the effects of hadronization do not destroy this agreement. However, putting that puzzle aside, let us note that the theoretical predictions shown are somewhat different for pion and proton beams, since the partonic structure functions are different. It will be interesting to see if further analysis of the data (including D^0 and $\overline{D}^0$) shows that the pion beam prediction is a better fit to the pion beam data than the proton beam prediction, and similarly for the proton beam data. This would show an experimental sensitivity to the partonic distributions and, possibly, a way to measure them, providing that the effect of fragmentation could be understood or is small.

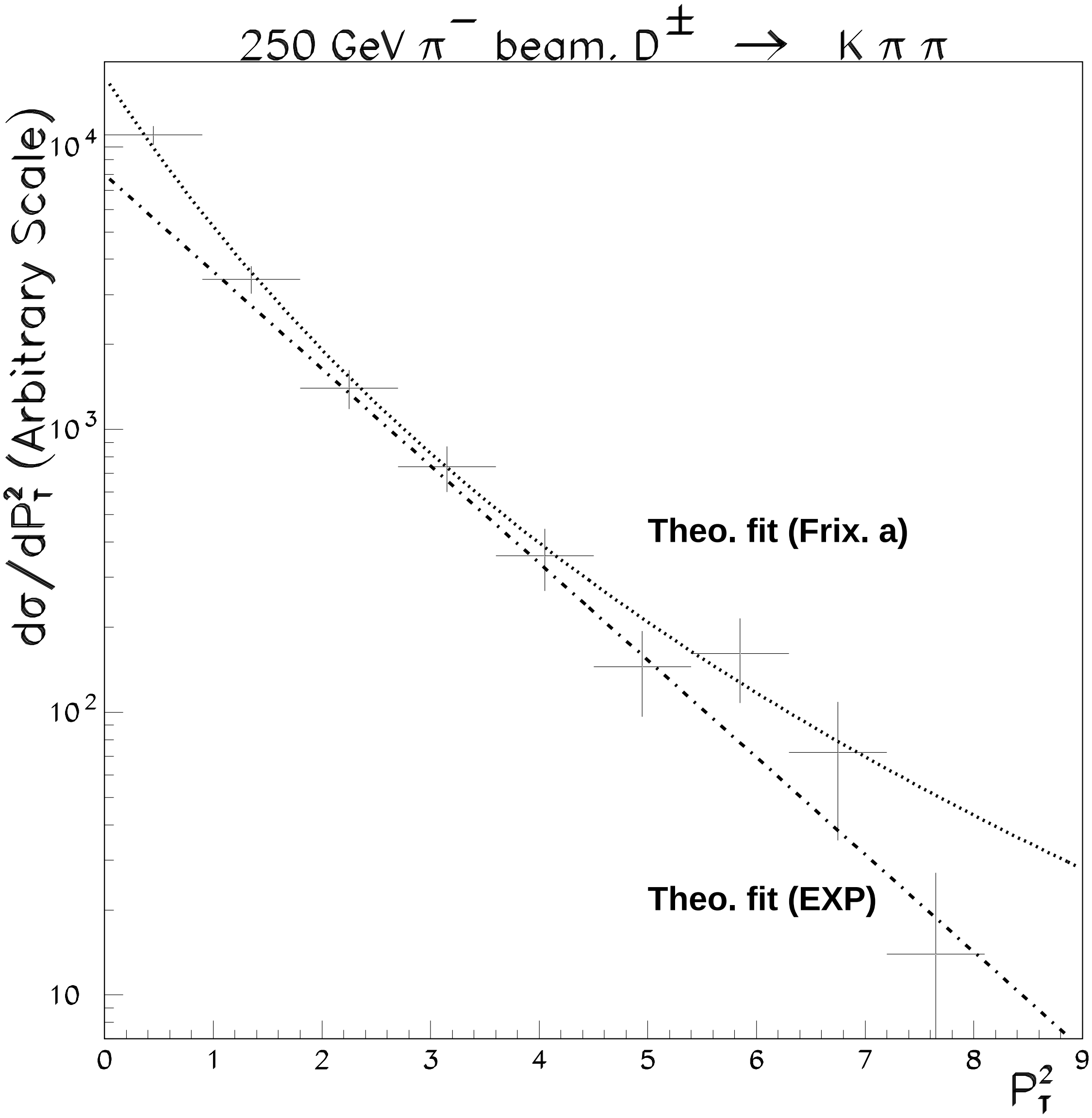

Figure 6: Comparison of E769 data with theory. The theoretical curves from Frixione et al. are normalized to give the best fit to the data. Otherwise, the parameters are fixed from the NLO QCD prediction for quarks. Two theoretical forms are shown: "Frixione a" and "Exponential". The form "Frixione a" is described in the text. The "Exponential" is a simple exponential function. The unit of P_T^2 is GeV^2.

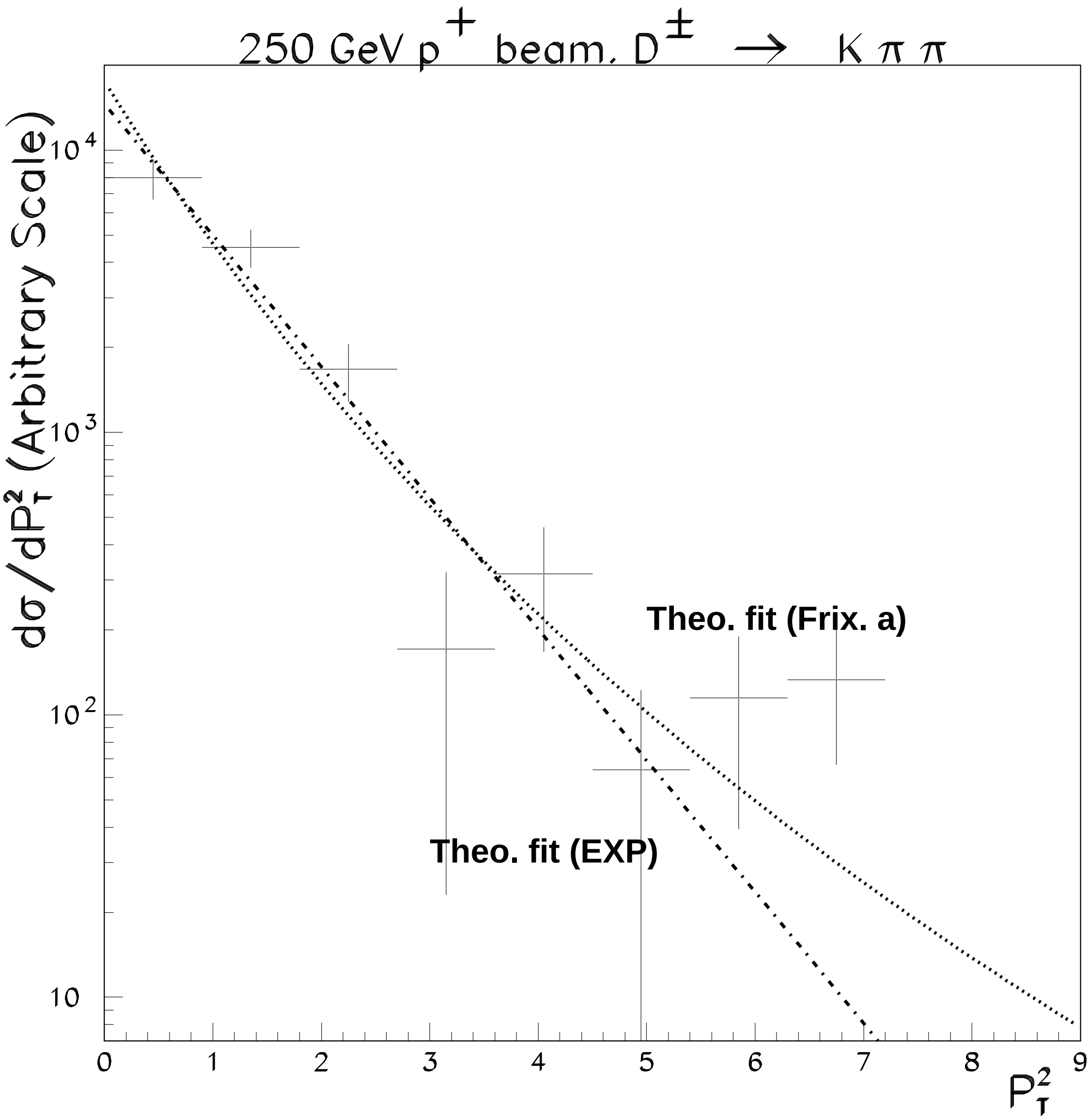

Figure 7: Same as Figure 6 but for a proton beam. The data are preliminary E769 results.

Correlations

The correlations of the kinematic variables of the charm and anti-charm particles provide another measure of the production process. A correlation with appealing simplicity is the angle $\delta\phi$ between charm particles in the plane transverse to the beam direction. This angle would be 180 degrees for the charm quarks produced in the two body process $gg \rightarrow c\bar{c}$ provided the gluons have no transverse momentum. The angular distribution becomes smeared, compared to a delta function at 180 degrees, when the effects are taken into account for higher order diagrams, intrinsic partonic p_T and charm quark hadronization.

Recent preliminary data on $\delta\phi$ from CERN WA92 are derived from its unique vertex detector: closely spaced silicon microstrip planes that provide measurements between the production vertex and the charm decay vertices. The measurement is based on 102 events in which one charm particle is fully reconstructed and the other is partially reconstructed, but with its decay vertex measured. The accuracy on $\delta\phi$ is typically 1 degree. The distribution of $\delta\phi$ is well fit by the NLO QCD prediction for quarks, including an intrinsic partonic p_T characterized by $< p_T^2 > \sim 0.3$ GeV^2. The WA92 distribution is similar to that measured in photoproduction, but differs from the somewhat broader distributions measured by other hadroproduction experiments, NA32 and WA75, which require $< p_T^2 > \sim 1 - 2$ GeV^2 for the partons.

Leading Asymmetry

Experiments WA82 [18] and E769 [19] established that there is a large hadroproduction asymmetry favoring leading over non-leading particles at large x_F. E769 found that the asymmetry, integrated over $x_F > 0$, is small over the measured range of p_T. Thus, the asymmetry is primarily associated with large x_F. The behavior of the asymmetry versus p_T, restricted to large x_F, would provide further details of the mechanism responsible.

There is a recent preliminary measurement of the asymmetry for $D^{\pm}$ production with a π^- beam from Fermilab E791 [20] based on approximately 9000 events. The asymmetry is reported for $p_T^2 < 10$ GeV^2 in three ranges of x_F: -.1 to .1, .1 to .3 and .3 to .7. These data confirm the previously established behavior of increasing asymmetry with x_F at low p_T. In addition, for the range of x_F centered about 0, these data indicate increased asymmetry at high p_T. For the other ranges of x_F, the data are consistent with no dependence of asymmetry on p_T.

Future Directions

Perhaps the most striking feature of the experimental data on hadronic charm cross sections is the lack of precise measurements! For example, to test the energy dependence of the total charm cross section there are only a few measurements with total error less than about 10%. Furthermore, there are *no* measurements over a broad range of x_F and p_T for $\sqrt{S} > 40$ GeV. Since the prediction for the total charm cross section is not affected by fragmentation, it is important to make cross section measurements for both the charm mesons and baryons.

The feature of the differential cross sections that might most aid our understanding of fragmentation is the large leading particle effect at high x_F. Measurements with much higher statistics than currently available are needed. The further analysis of the CERN WA89 data will help. Also, the Fermilab SELEX experiment (E781), scheduled to take data in 1996, has large acceptance at high x_F and should be able to study the leading particle effect with a variety of beams (Σ^-, π^- and p) and large samples of charm mesons and baryons.

Other planned experiments are also expected to make new measurements of charm hadroproduction. In his talk at this conference, H. Siebert reported that the WA89 collaboration may take additional data with beams other than Σ^-. The HERA-B experiment at DESY is designed primarily for beauty measurements, but should be able to make substantial measurements of charm production. At RHIC, charm production measurements in heavy ion collisions are part of the program to study the quark gluon plasma. Measurements with $p-p$ collisions are a necessary part of this program. Perhaps a new fixed target experiment at Fermilab will be dedicated to study charm, as advocated by Dan Kaplan at this conference.

Charm hadroproduction is an area where basic experimental measurements can have a big impact. We still must identify the basic mechanisms, perhaps using QCD combined with fragmentation models, that will explain the data. We look forward with great interest to further analysis of the existing data, the results of future experiments, and further progress in our theoretical understanding.

Acknowledgements

The author is indebted to his colleagues of the E769 experiment, especially Andrew Wallace, Hélio da Motto Filho, and Chris Kennedy who prepared the new preliminary results from E769 presented here. We thank Giovanni Ridolfi for the computer program to generate the charm cross sections predicted by NLO QCD. Thanks also to Leonardo Rossi who communicated results from the CERN WA92 experiment and Jeff Appel who organized the charm session. We gratefully acknowledge funding from the U.S. Department of Energy.

References

[1] J.A. Appel, "Hadroproduction of Charm Particles", Annu. Rev. Nucl. Part. Sci. 42

(1992) p. 367.

[2] S. Frixione, M.L. Mangano, P. Nason and G Ridolfi, "Charm and Bottom Production: Theoretical Results Versus Experimental Data", Nucl. Phys. B 431 (1994) p. 453.

[3] S. Barlag et al. (ACCMOR Collaboration), "Production of D, D^* and D_s mesons in 200 GeV/c π^-, K^- and p-Si interactions", Z. Phys. C 39 (1988) p. 451.

[4] S. Barlag et al. (ACCMOR Collaboration), "Production properties of D^0, D^+, D^{*+} and D_s^+ in 230 GeV/c π^- and K^- - Cu interactions", Z. Phys. C 49 (1991) p. 555.

[5] L. Rossi, private communication, and M. Adamovich et al., to be submitted to Phys. Lett. B.

[6] M. Aguilar-Benitez et al. (NA27 LEBC-EHS Collaboration), "Inclusive Properties of D Mesons Produced in 360 GeV $\pi^- p$ Interactions", Phys. Lett. 161B (1985) p. 400.

[7] K. Kodama et al. (Fermilab E653 Collaboration), "Charm meson production in 600 Gev/c π^- emulsion interactions", Phys. Lett. B 284 (1992) p 461.

[8] M. Aguilar-Benitez et al. (NA16 LEBC-EHS Collaboration), "D Meson Branching Ratios and Hadronic Charm Production Cross Sections", Phys. Lett. B 135 (1984) p. 237.

[9] M. Aguilar-Benitez et al. (NA27 LEBC-EHS Collaboration), "Charm hadron properties in 400 GeV/c pp interactions", Z. Phys. C 40 (1988) P. 321.

[10] K. Kodama et al. (Fermilab E653 Collaboration), "Charm meson production in 800 Gev/c proton emulsion interactions", Phys. Lett. B 263 (1991) p 573.

[11] R. Ammar et al. (LEBC-MPS Collaboration), "D-Meson Production in 800-GeV/c pp Interactions", Phys. Rev. Lett. 61 (1988) p. 2185.

[12] M.J. Leitch et al., (Fermilab E789 Collaboration), "Nuclear Dependence of Neutral D-Meson Production by 800 GeV/c Protons", Phys. Rev. Lett. 72 (1994) p. 2542.

[13] M. Aguilar-Benitez et al. (NA27 LEBC-EHS Collaboration), "Neutral and Charged D* Production in 360 GeV/c $\pi^- p$ Interactions", Phys. Lett. 161B (1985) p. 400.

[14] S. Barlag et al. (ACCMOR Collaboration), "Production of the charmed baryon Λ_c^+ in π^-Cu and K^-Cu interactions at 230 GeV", Phys. Lett. B 247 (1990) p. 113.

[15] M. Adamovich et al. (WA82 Collaboration), "Nuclear Dependence of Charm Production by a 340 GeV π^- beam", Phys. Lett. B 284 (1992) p. 453.

[16] J. Anjos et al. (E769 Collaboration), "Atomic Mass Dependence of $D^\pm$ and $D^0, \overline{D}^0$ Production in 250 GeV $\pi^\pm$-Nucleon Interactions", Phys. Rev. Lett. 70 (1993) p. 722.

[17] G.A. Alves et al. (E769 Collaboration), "Feynman-x and Transverse Momentum Dependence of $D^\pm$ and $D^0, \overline{D}^0$ Production in 250 GeV $\pi^\pm$-Nucleon Interactions", Phys. Rev. Lett. 72 (1994) p. 812.

[18] M. Adamovich et al. (WA82 Collaboration), Study of D^+ and D^- Feynman's x distributions in π^--nucleus interactions at the SPS", Phys. Lett. B 305 (1993) p. 402.

[19] G.A. Alves et al. (E769 Collaboration), "Enhanced Leading Production of $D^\pm$ and $D^{*\pm}$ in 250 GeV $\pi^\pm$-Nucleon Interactions", Phys. Rev. Lett. 72 (1994) p. 812.

[20] J.A. Appel, "New Preliminary Results on the Physics of Charm Hadroproduction Subprocesses", FERMILAB-Conf-94/347-E, to appear in the Proceedings of the International Conference on High Energy Physics, Glasgow, Scotland, July, 1994.